New insights into the structure of ^{3}He

Measurement of double-polarized asymmetries in quasi-elastic processes $^3\overrightarrow{\mathrm{He}}(\vec{e},e'd)$ and $^3\overrightarrow{\mathrm{He}}(\vec{e},e'p)$

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For the E05-102 Collaboration

Jefferson Lab

My First Big Talk

Why study ^{3}He?

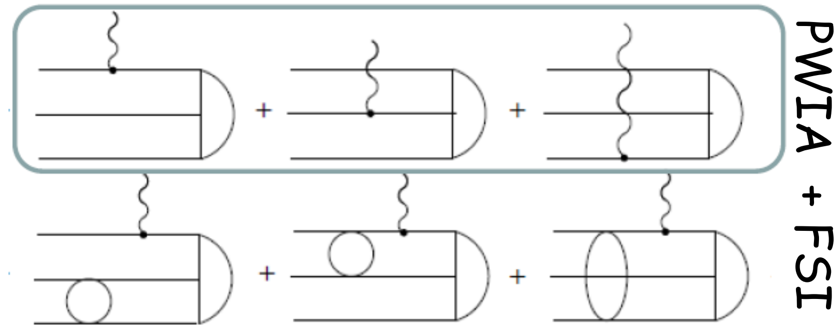
^{3}He is interesting because it is a calculable nuclear system, where theoretical predictions of its nuclear structure can be compared with data to an increasingly accurate degree.

To obtain a good agreement between theory and data, a precise understanding of following items is required:

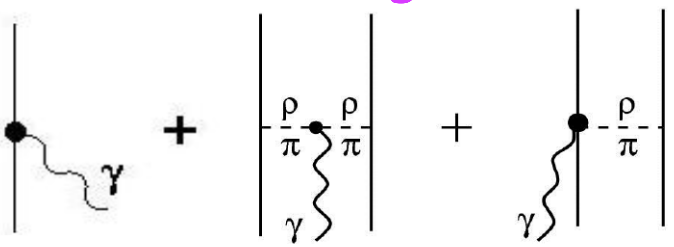
^{3}He ground state wave function

$$\psi_{GS} = \psi' + \psi'' + \psi''' + \cdots$$

Final-State Interactions

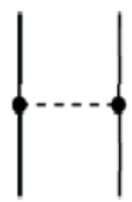


Meson Exchange Currents

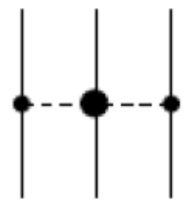


Nuclear forces

2NF:



3NF:



^{3}He as effective n target

Detailed knowledge on **structure of ^{3}He is crucial** for extracting precise information on **neutron structure**.

- **Proton** is well known and its properties are precisely measured.
- **Neutron** not understood to a desirable accuracy, especially charge, and spin distribution

Problem: no neutron target, direct measurements not possible.

Solution: indirect measurements using appropriate targets:

1.) **Deuteron**

2.) **^{3}He**

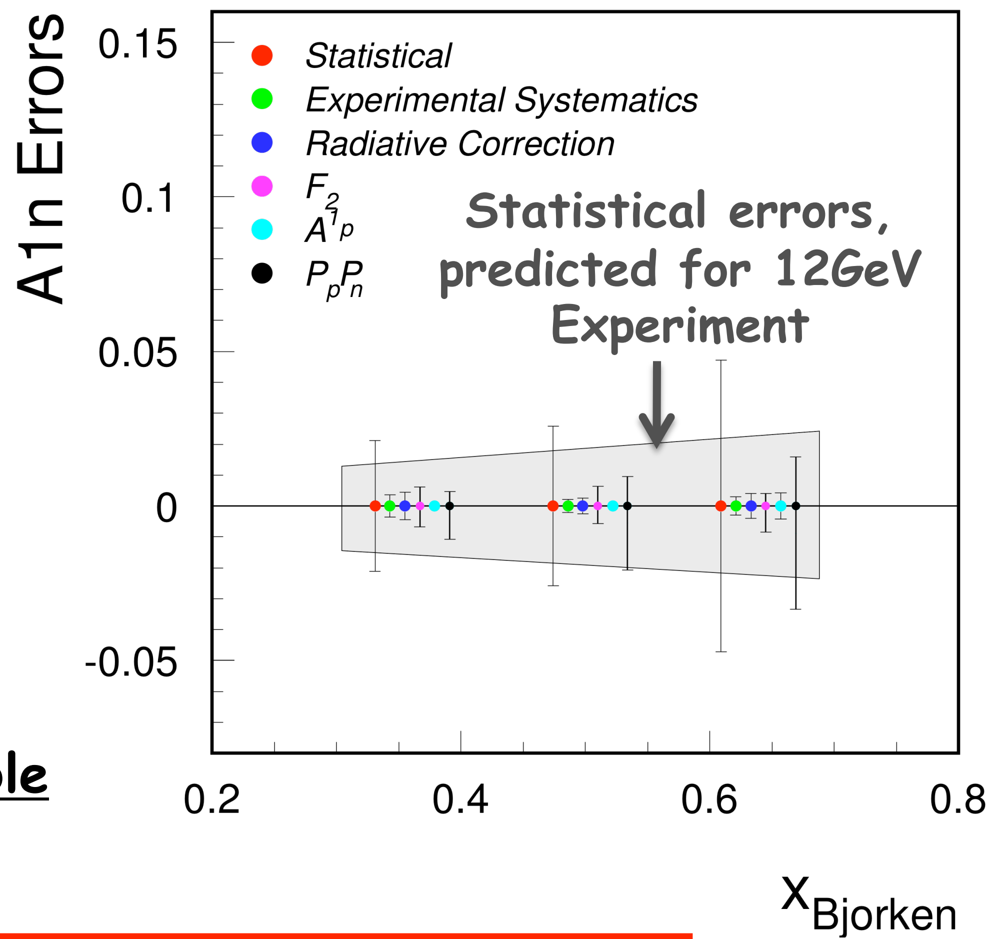
How detailed should this knowledge be?

Measurements of neutron spin asymmetry A_1^n (experiment E99-117), important for understanding **n** spin structure:

Main sources of errors:

- Statistical uncertainty
- uncertainty of the proton and neutron polarization

Depends directly on structure of polarized ^3He



PROBLEM: **Statistical error of the 12GeV experiment comparable to the polarization uncertainty**

Urgent need for better knowledge on structure of ^3He !

^{3}He ground-state wave-function

- A bound state of **p,p,n**: **$S = \frac{1}{2}$, $T = \frac{1}{2}$ ($M_T = +\frac{1}{2}$)**
- The Faddeev calculations for the ground-state WF predict:

Table 1.1 — The partial wave channels of the three-nucleon (α, β, γ) wave function within the Derrick-Blatt scheme [3]. S and L are the spin and the angular momentum of ^{3}He. l_α is the relative orbital angular momentum of the pair ($\beta\gamma$), while L_α represents the orbital angular momentum of the ($\beta\gamma$) center of mass relative to α, with $\vec{L} = \vec{l}_\alpha + \vec{L}_\alpha$. P and K label the basis vectors $|PK\rangle$ of the irreducible representations of the permutation group S_3, which are considered for description of the three-nucleon spin states.

Channel number	L	S	l_α	L_α	P	K	Probability (%)	WF State
1	0	0.5	0	0	A	1	87.44	S
2	0	0.5	2	2	A	1	1.20	S
3	0	0.5	0	0	M	2	0.74	S′
4	0	0.5	1	1	M	1	0.74	S′
5	0	0.5	2	2	M	2	0.06	S′
6	1	0.5	1	1	M	1	0.01	P
7	1	0.5	2	2	A	1	0.01	P
8	1	0.5	2	2	M	2	0.01	P
9	1	1.5	1	1	M	1	0.01	P
10	1	1.5	2	2	M	2	0.01	P
11	2	1.5	0	2	M	2	1.08	D
12	2	1.5	1	1	M	1	2.63	D
13	2	1.5	1	3	M	1	1.05	D
14	2	1.5	2	0	M	2	3.06	D
15	2	1.5	2	2	M	2	0.18	D
16	2	1.5	3	1	M	1	0.37	D

- Calculations predict WF to be dominated by **S**, **D** and **S'** states.

- Other states (P) can be neglected.

^{3}He ground-state wave-function

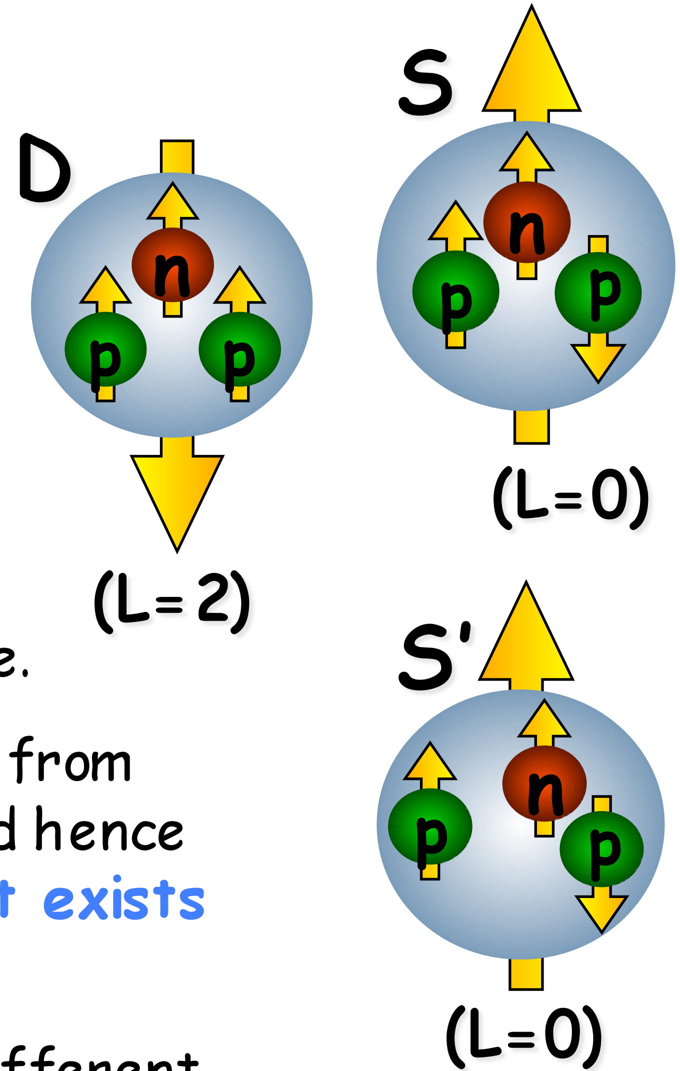
1.) **Spatially symmetric state S (90%):** Protons are in spin-singlet state. ^{3}He spin is dominated by spin of **n**. Therefore ^{3}He can be used as an effective **n** target:

$$\frac{\mu_{^3He}}{\mu_n} = \frac{-2.131}{-1.913} \approx 1$$

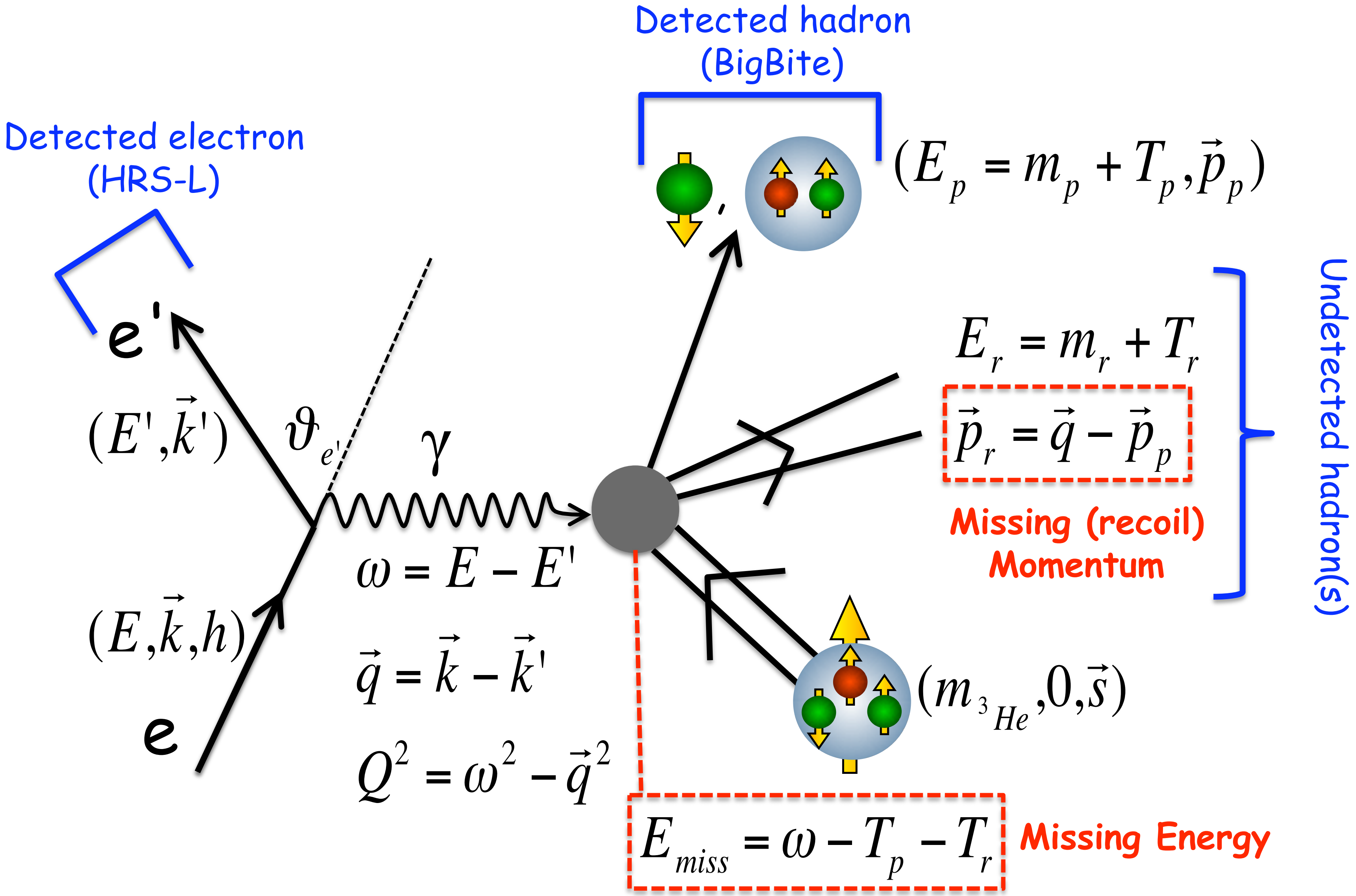
2.) **State D (8%):** Nucleon spins oriented opposite to the ^{3}He nuclear spin. Generated by tensor component of NN force.

3.) **Mixed symmetry state S' (2%):** Arises from differences between T=0 and T=1 forces and hence reflects (spin-isospin)-space correlations. **It exists only for ^{3}He and ^{3}H.**

The difference in their radii explained by different probabilities for S' state (P_{triton}~1%)



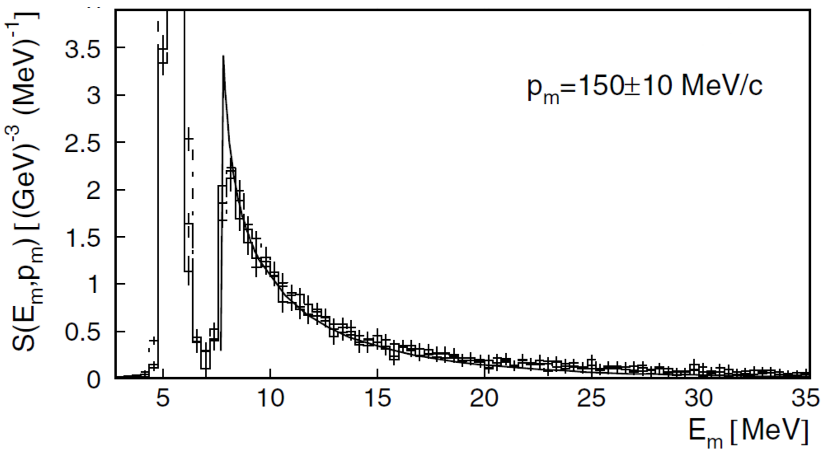
Electron scattering on ^{3}He



Previous Experiments #1

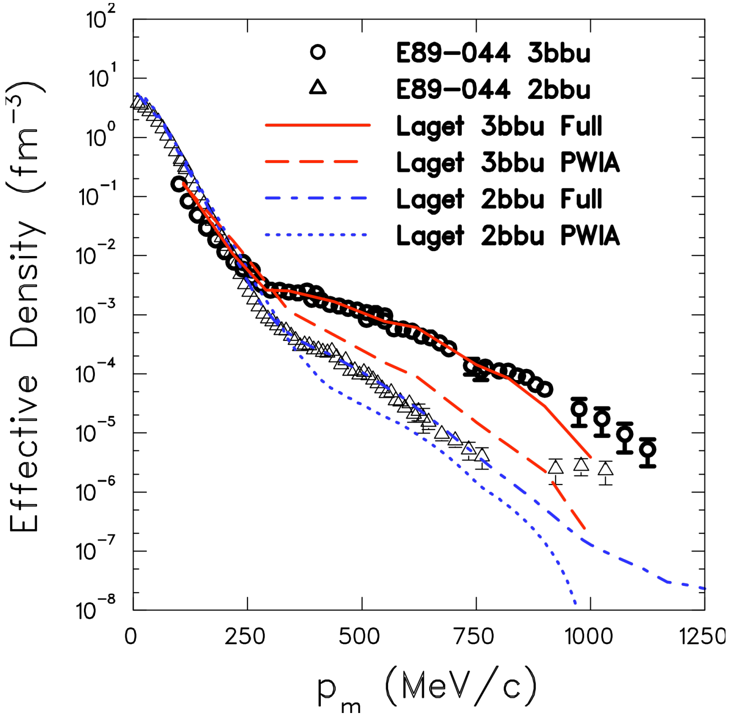
Precision measurements at low Q^2

- MAMI experiments
- Low missing momentum region
- Clear separation of 2BBU and 3BBU
- Studied QE region (Florizone) and region <QE (Kozlov)
- Discrepancy between the theory and measurements remains



Measurements at high Q^2

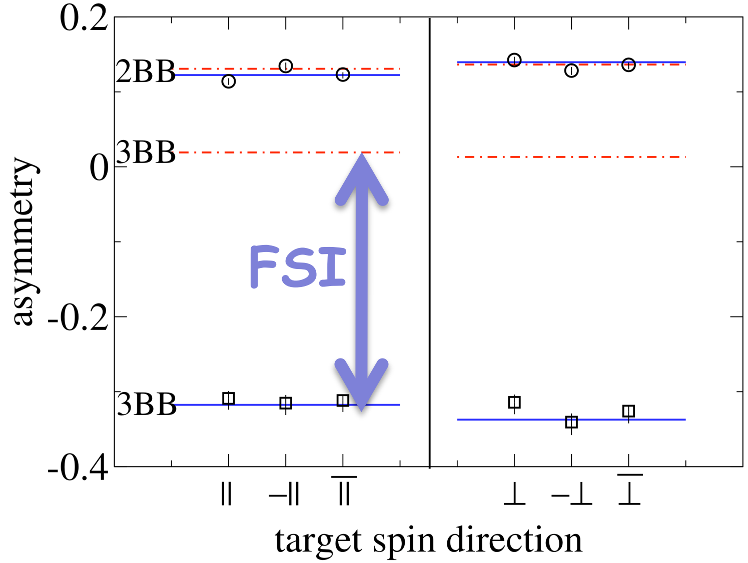
- JLab exp. (Benmokhtar, Rvachev)
- Tremendous range of miss. mom.
- Fixed (ω, q)



Previous Experiments #2

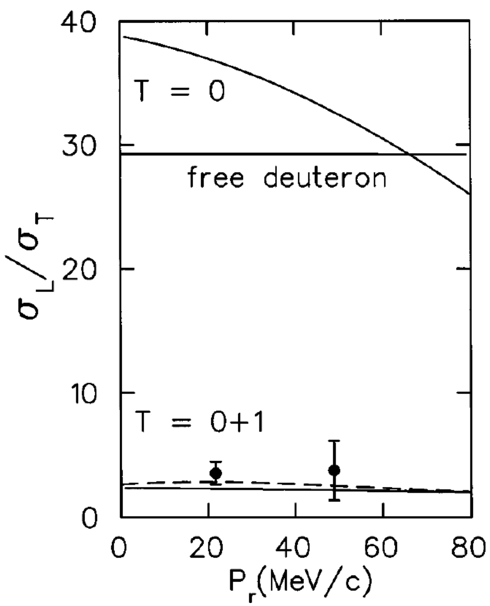
Double-polarization experiments:

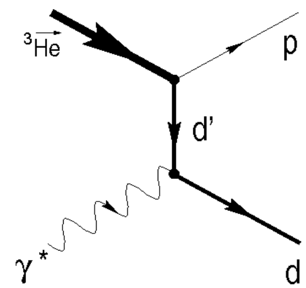
- MAINZ exp. (Achenbach, Carasco)
- Reactions $^3\vec{He}(\vec{e},e'p)d$, $^3\vec{He}(\vec{e},e'p)pn$
- Study of FSI effects
- Reaction $^3\vec{He}(\vec{e},e'd)$ still unexplored (first attempts at NIKHEF)

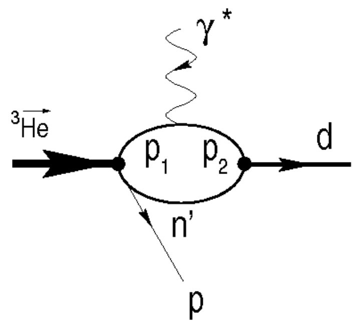


Important Milestones:

- MIT-Bates (Tripp):
  Measured $^3He(e,e'd)$ and showed that both isoscalar and isovector current are needed.
- IUCF (Milner):
  Double Pol.Asym. in $^3\vec{He}(\vec{p}, 2p)$, $3\vec{He}(\vec{p},pn)$; Weakness of hadronic probes.
- NIKHEF (Poolman):
  Pilot measurement of $^3\vec{He}(\vec{e},e'p)$ and $^3\vec{He}(\vec{e},e'n)$; Comparison to PWIA.



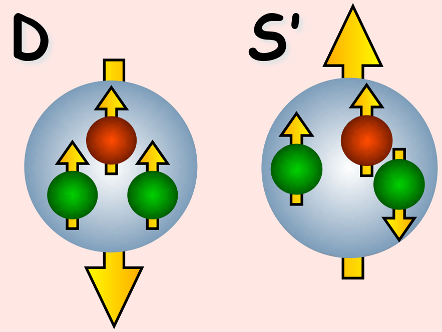




Benefits of Polarization

No. 1

- Polarization observables (asymmetries) accessible via double polarization experiments are very **sensitive to small components** of ground-state WF.



- Understanding the role of the **D** and ***S'*** states in ^{3}He is a very important aspect of the few-body theory.

- Properties of D and S′ state **can not be accessed via XS measurements** in un-polarized experiments.

No. 2

- Measuring asymmetries saves a lot of problems, because "all" the **problems with normalization of cross-section disappear**.

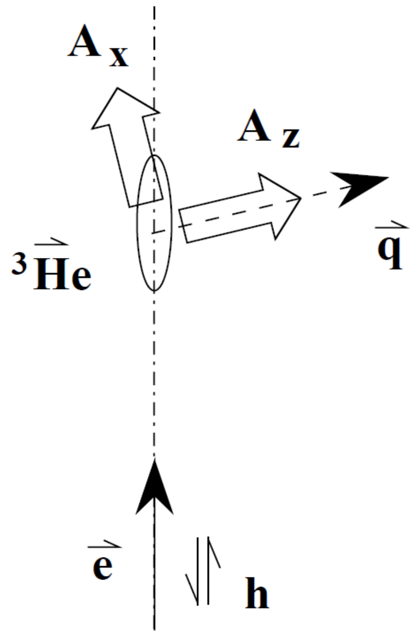
A_x, A_z Asymmetry Measurement
and experiment E05-102

- Observables sensitive to the **D, S'** state constitute a stringent test of the theory. Among them are also asymmetries **A_x** and **A_z**.

- For polarized beam and polarized target, the cross-section for the ^{3}He(e,e'd) is:

$$\frac{d\sigma(h,\vec{S})}{d\Omega_e\, dE_e\, d\Omega_d\, dp_d} = \frac{d\sigma_0}{d\Omega_e\, dE_e\, d\Omega_d\, dp_d}\left[1+\vec{S}\cdot\vec{A}^0 + h(A_e+\vec{S}\cdot\vec{A})\right]$$

$$A_{x,z} = \frac{[d\sigma_{++}+d\sigma_{--}]-[d\sigma_{+-}+d\sigma_{-+}]}{[d\sigma_{++}+d\sigma_{--}]+[d\sigma_{+-}+d\sigma_{-+}]}$$



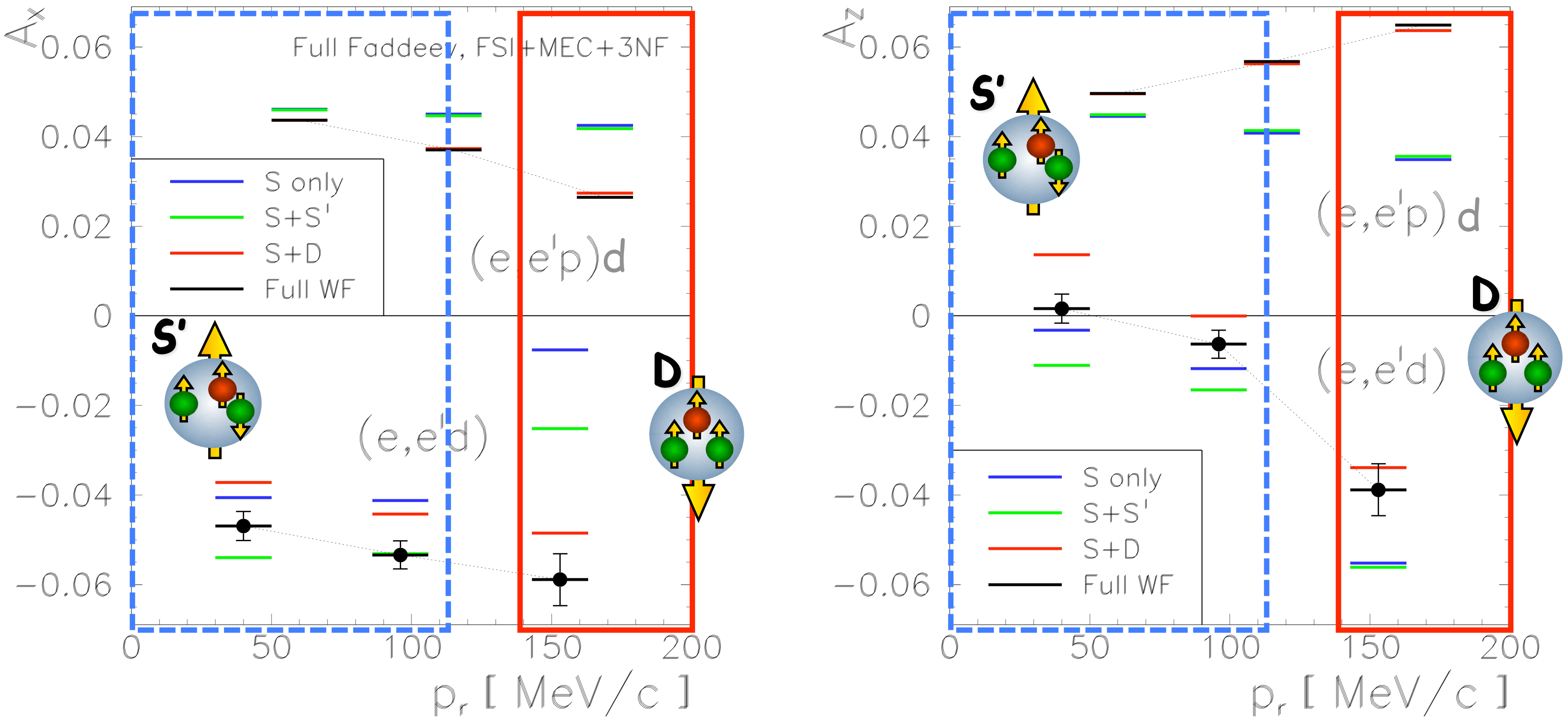
E05-102: Simultaneous measurement of asymmetries in **^{3}He(e,e'd)** and **^{3}He(e,e'p)** for recoil momenta between 0 and ~300MeV/c

What are the theoretical expectations?

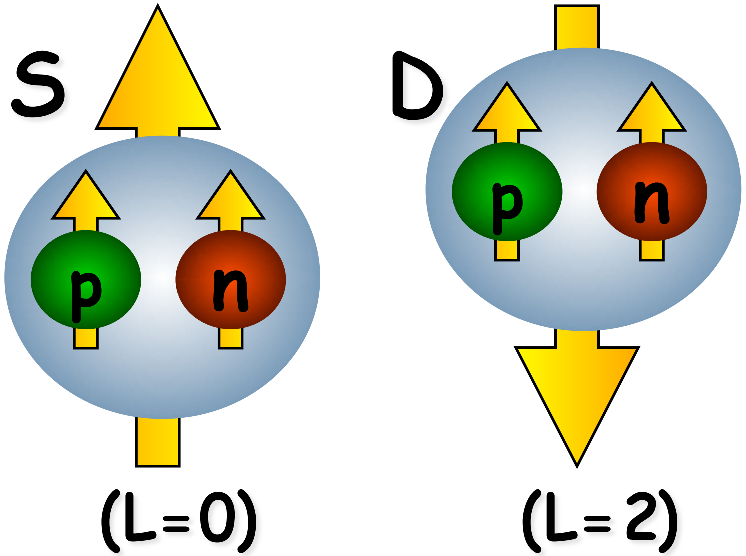
- State-of-the-art Faddeev calculations from: Krakow/Bochum, Pisa, Trento, Hannover/Lisboa groups.

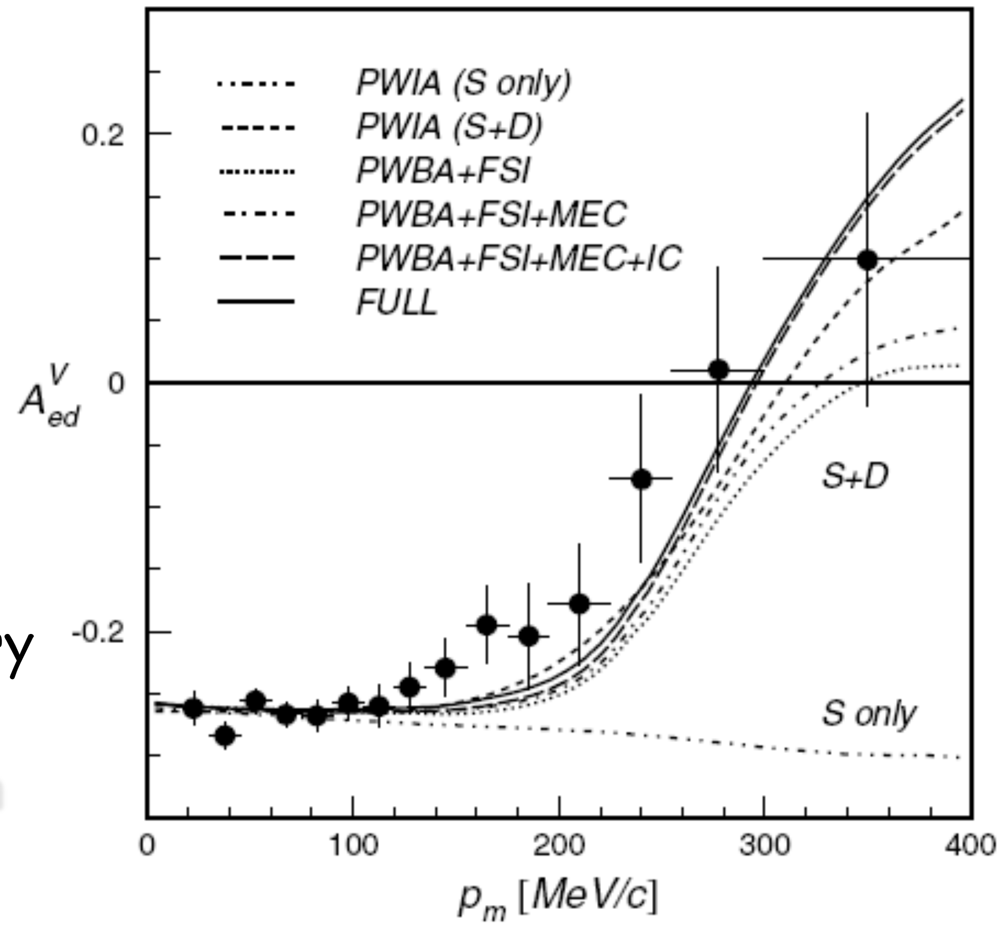
- The role of **S'** is most evident in region of <u>small recoil momenta</u> where A_x is large. A_z is close to zero at small p_r.

- Much stronger variation of A_z at high p_r: **Governed by the D-state.**



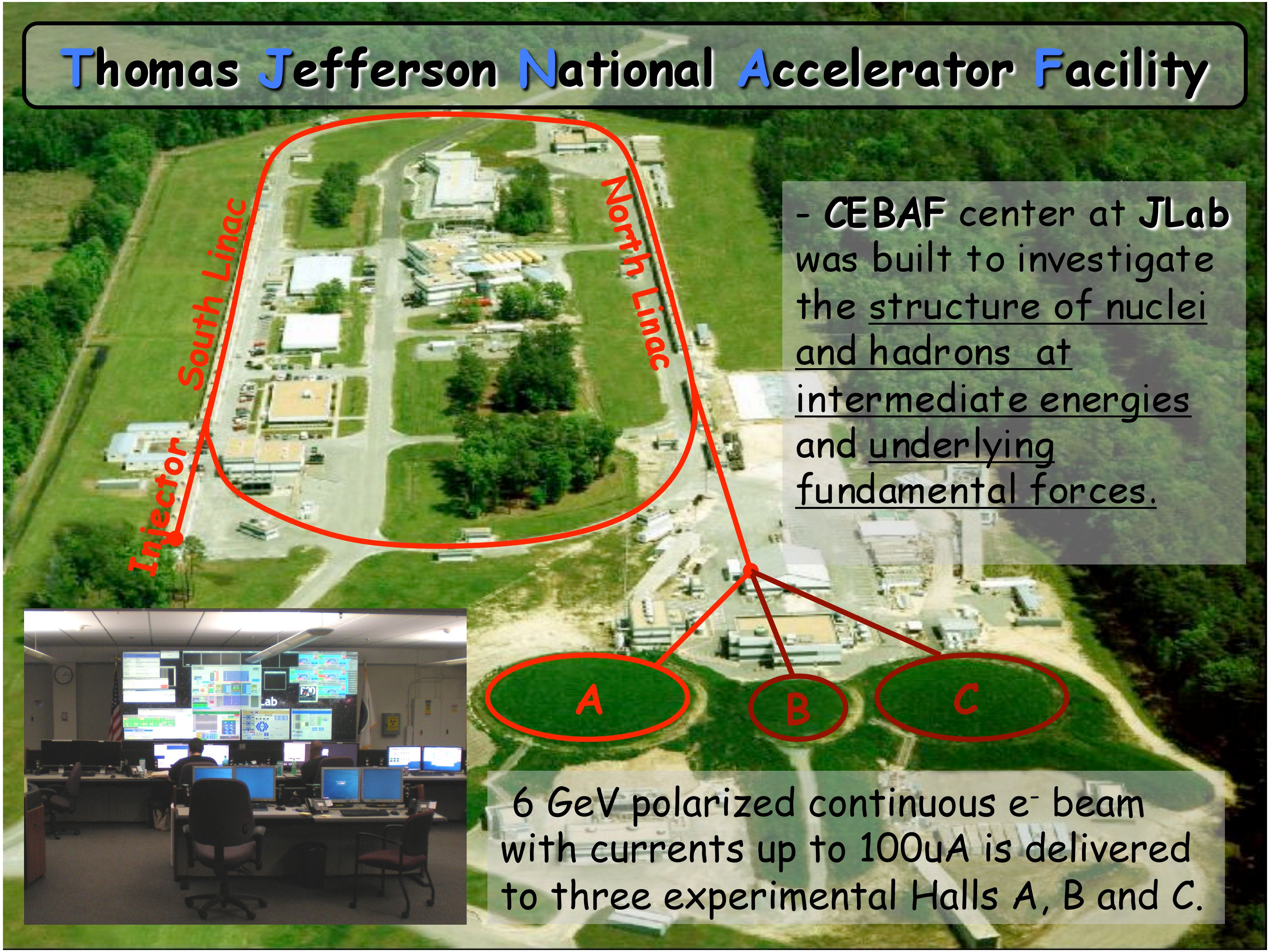
Results for $^2\vec{H}(\vec{e},e'p)n$ from NIKHEF





-Sign-change of the Asymmetry is a clear sign that **D-state component manifests itself in the nucleus at high p_{miss}.**

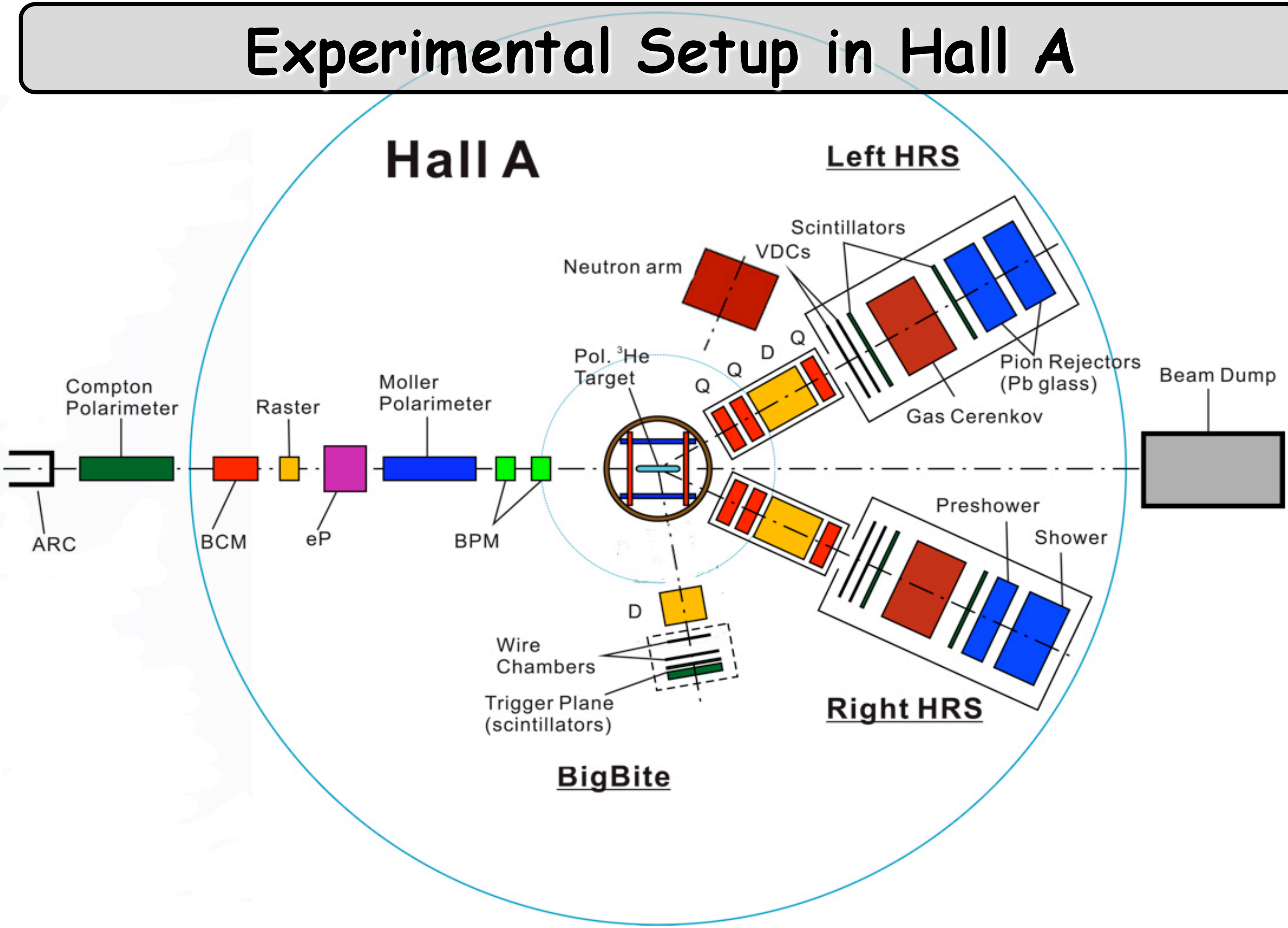
Thomas **J**efferson **N**ational **A**ccelerator **F**acility



- **CEBAF** center at **JLab** was built to investigate the <u>structure of nuclei and hadrons at intermediate energies</u> and <u>underlying fundamental forces.</u>

6 GeV polarized continuous e^- beam with currents up to 100uA is delivered to three experimental Halls A, B and C.

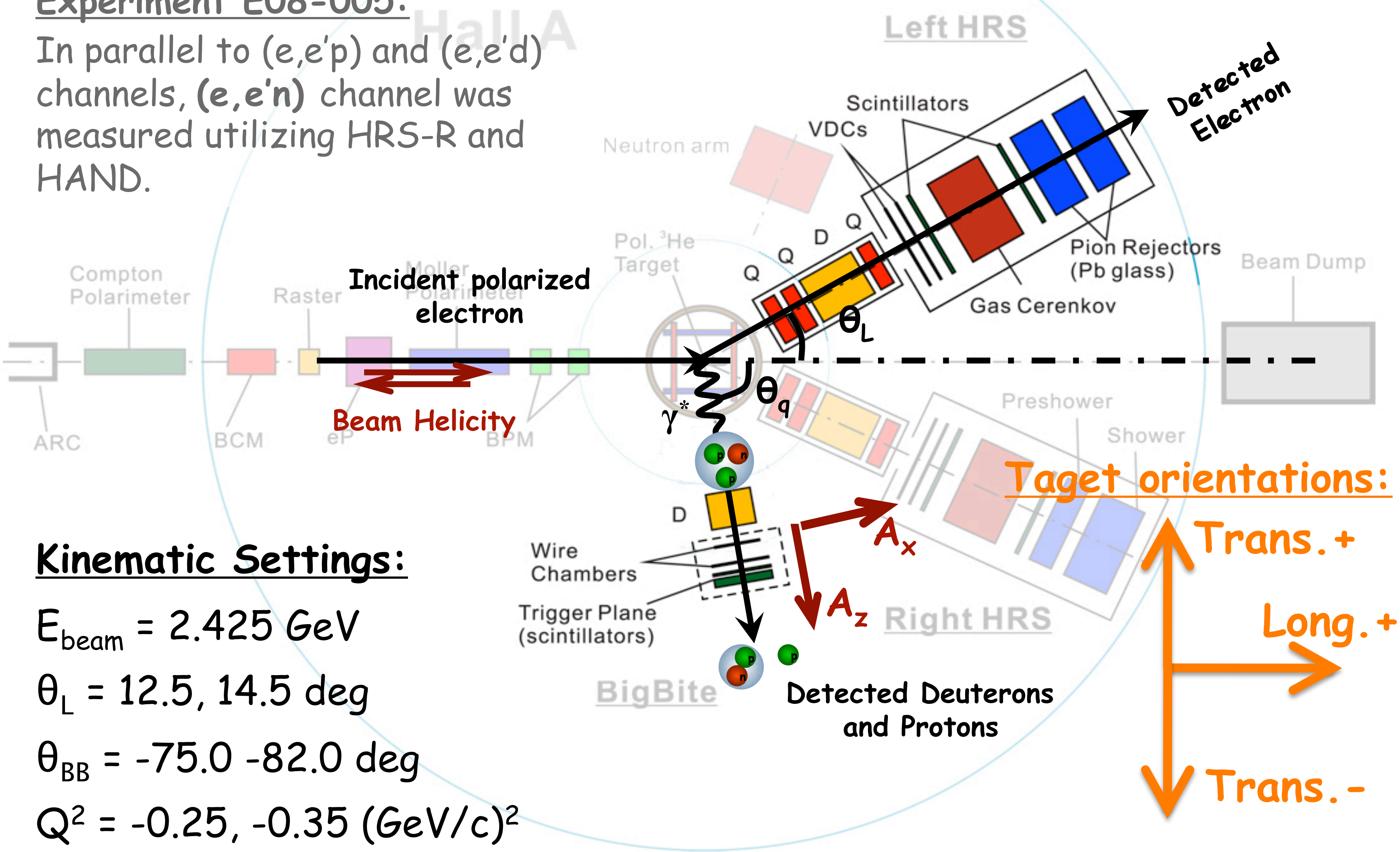
Experimental Setup in Hall A



Experiment E05-102 in Hall-A

Experiment E08-005:

In parallel to (e,e'p) and (e,e'd) channels, **(e,e'n)** channel was measured utilizing HRS-R and HAND.



Kinematic Settings:

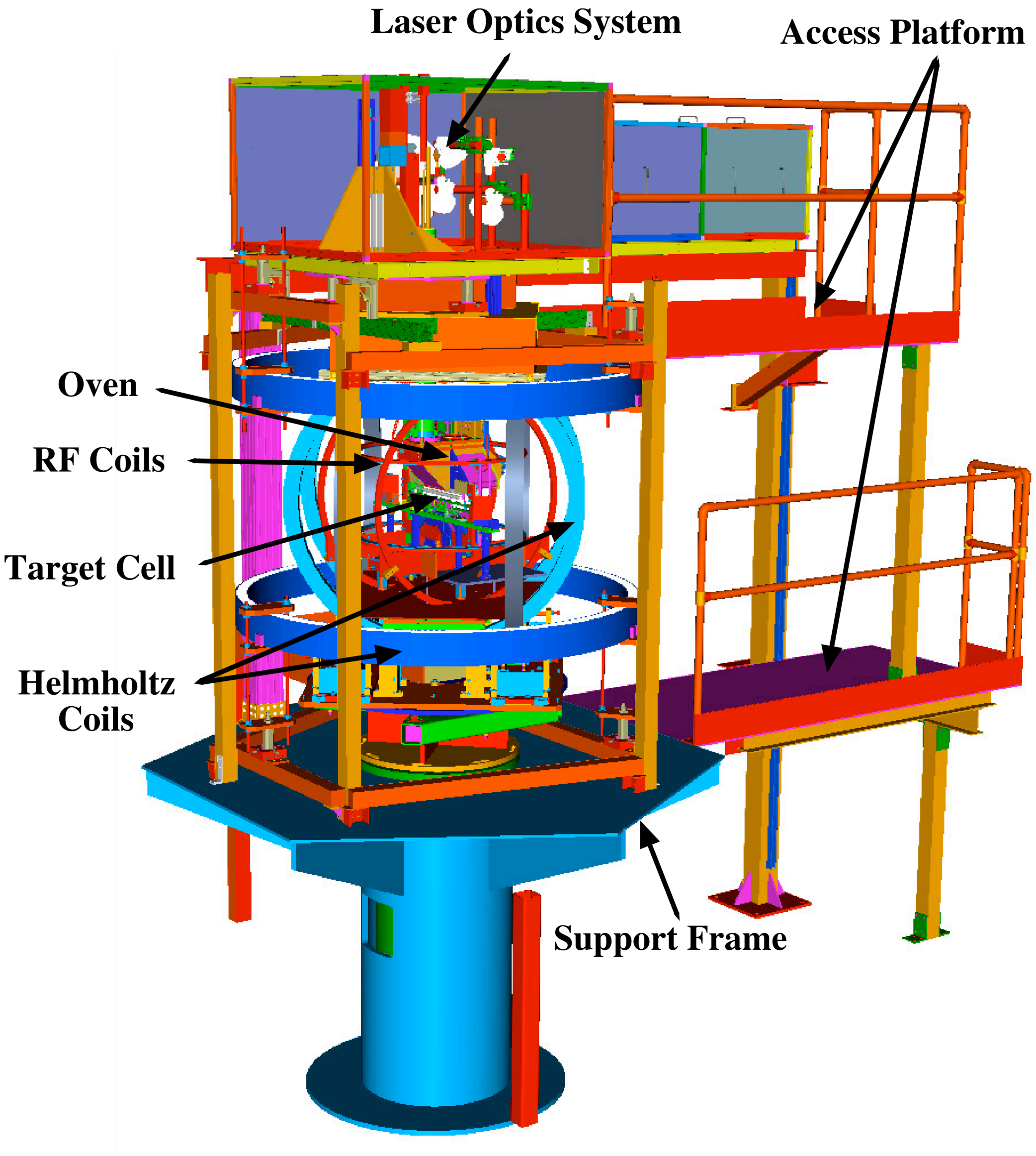
E_{beam} = 2.425 GeV

θ_L = 12.5, 14.5 deg

θ_{BB} = -75.0 -82.0 deg

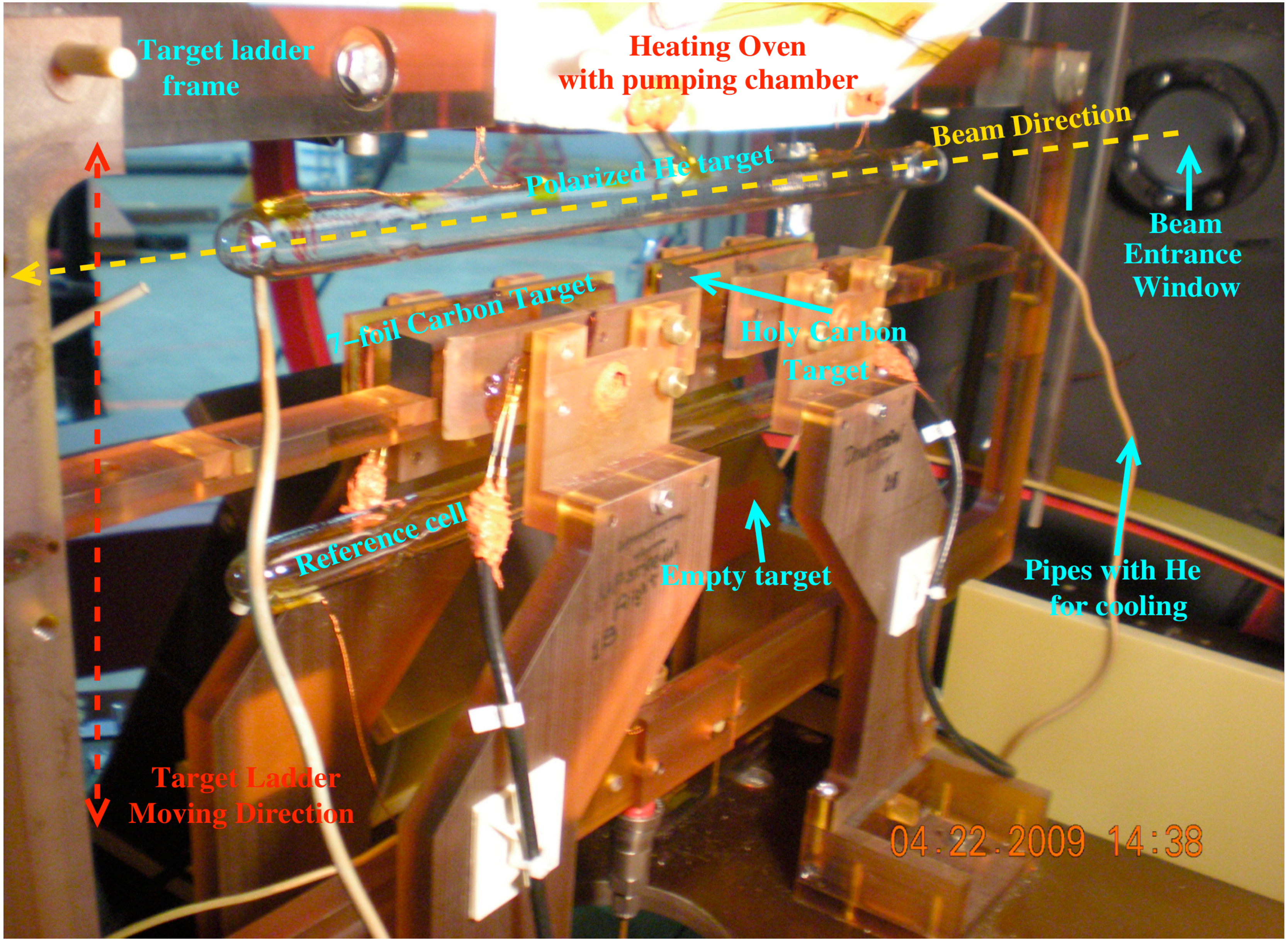
Q^2 = -0.25, -0.35 $(GeV/c)^2$

Polarized $^3\overrightarrow{He}$ Target System



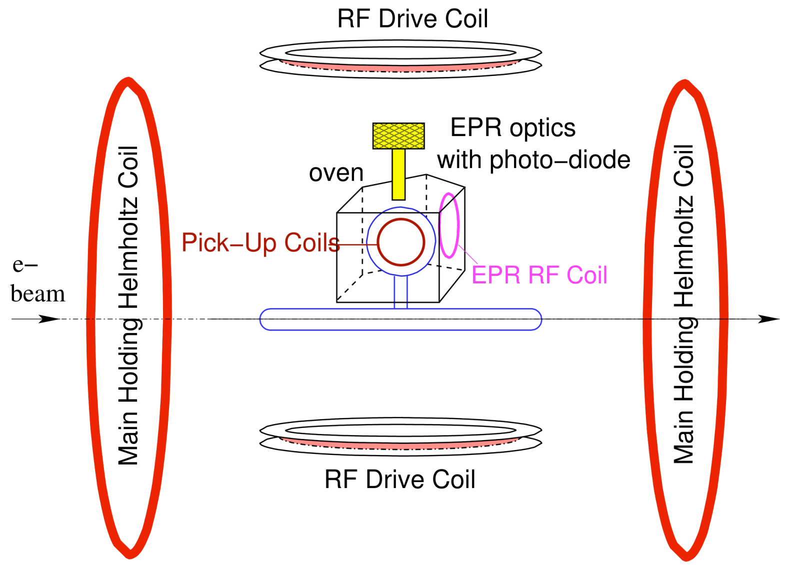
- Target ladder with targets
- Heating oven
- Five High-Power IR-Diode lasers (~30W) for polarizing the target in all three direction
- Optical table with lenses, mirrors, λ–shifters is used to guide light from optical fibers to the target.
- Three pairs of Helmholtz coils to hold spin in a particular direction
- Polarization measurement equipment

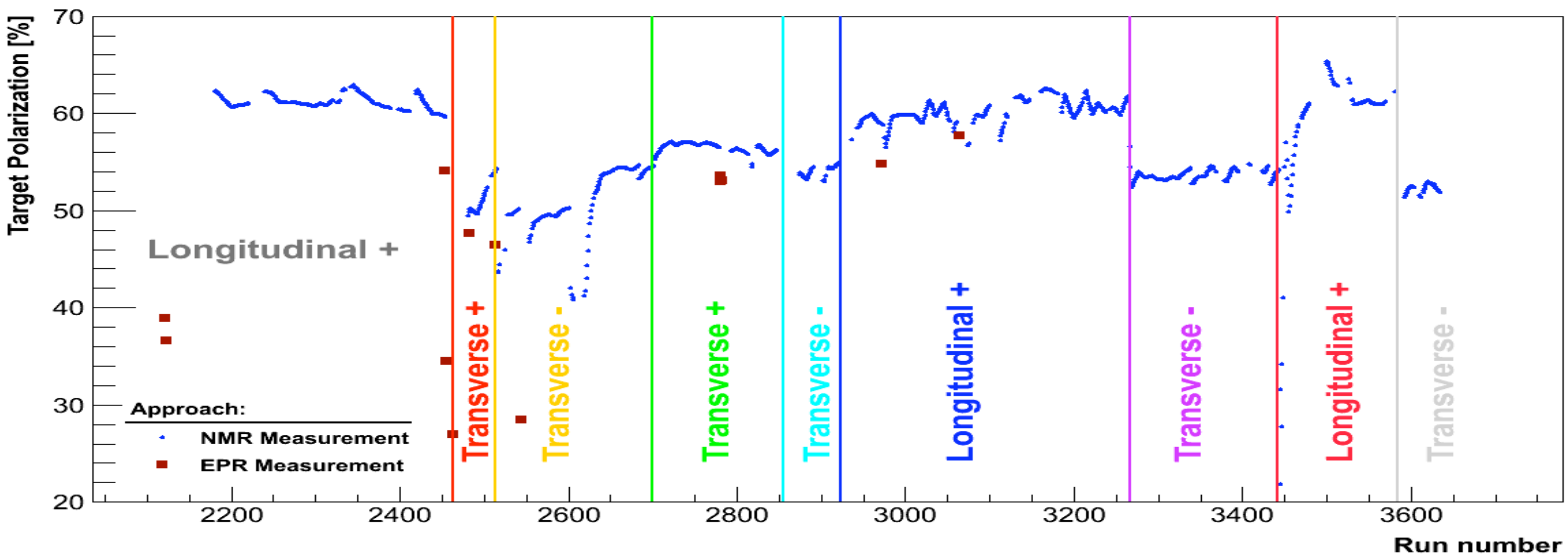
Target Ladder



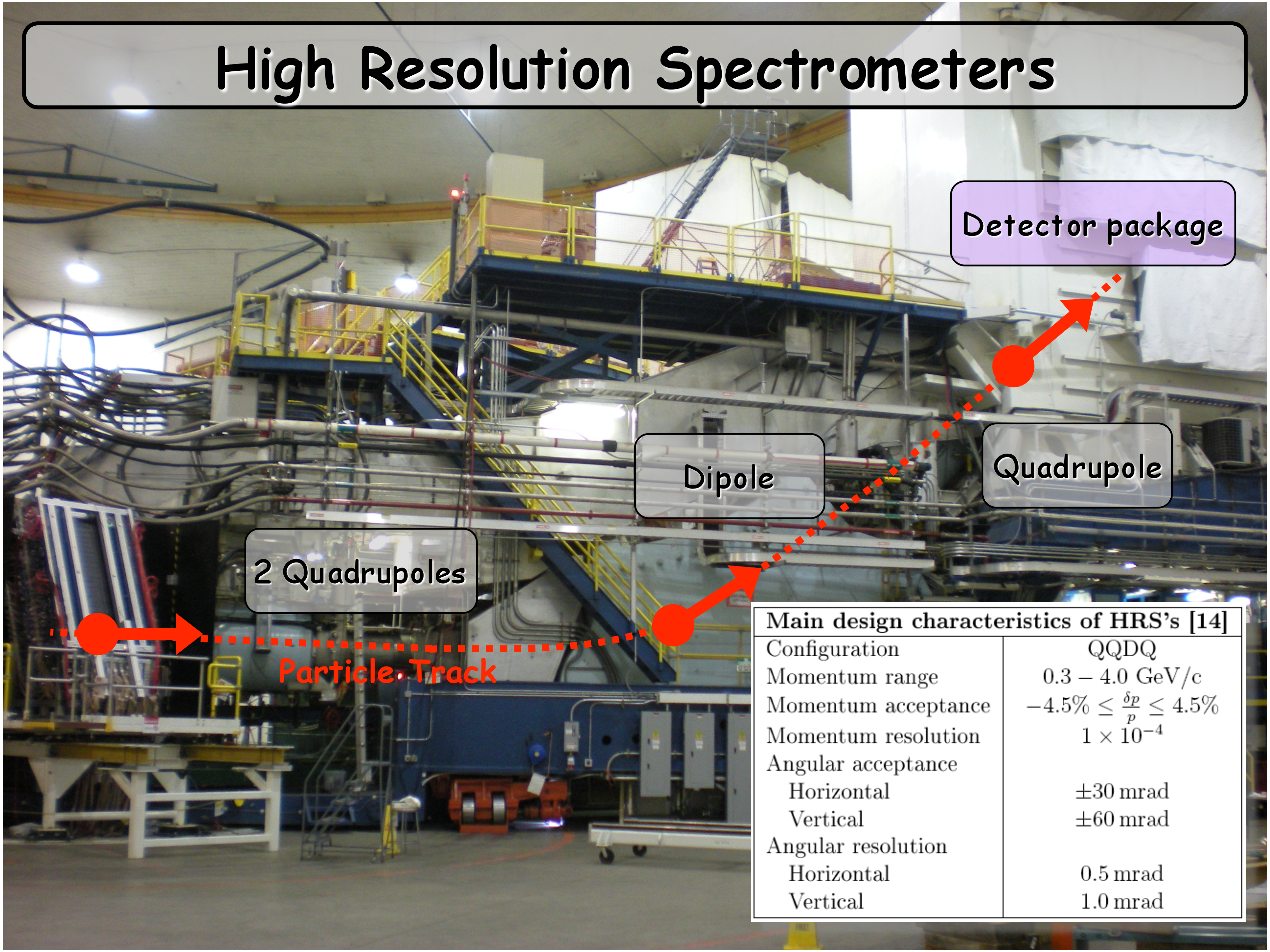
Polarization of the $^3\vec{He}$ Target

- The target polarization was constantly monitored (4hours)
- **NMR** (relative) and **EPR** (absolute) methods were utilized
- Polarization measured at the pumping chamber. Corrections needed.
- Polarization **~60%**





High Resolution Spectrometers



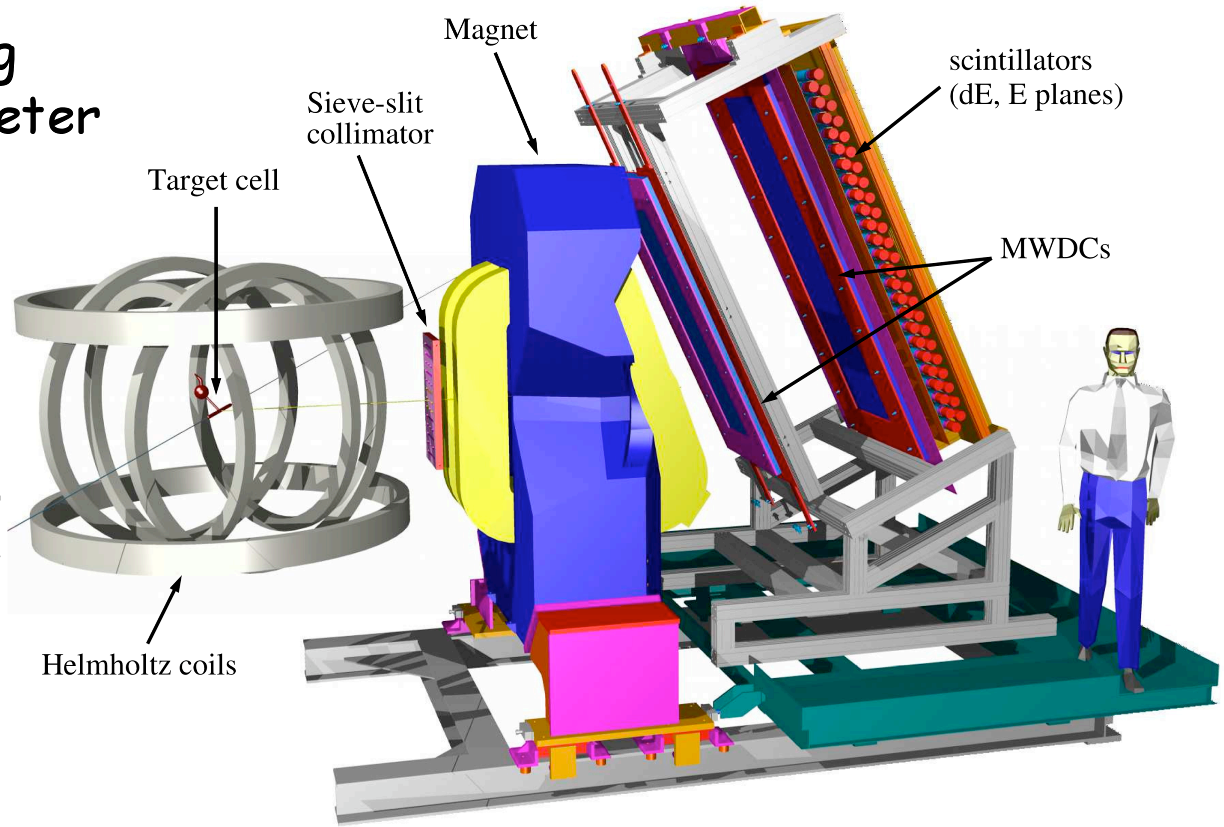
Main design characteristics of HRS's [14]	
Configuration	QQDQ
Momentum range	$0.3 - 4.0$ GeV/c
Momentum acceptance	$-4.5\% \leq \frac{\delta p}{p} \leq 4.5\%$
Momentum resolution	1×10^{-4}
Angular acceptance	
Horizontal	± 30 mrad
Vertical	± 60 mrad
Angular resolution	
Horizontal	0.5 mrad
Vertical	1.0 mrad

BigBite Spectrometer

- Single normal-conducting dipole magnet spectrometer

- Combines a large solid angle with a large momentum acceptance.

BigBite main characteristics	
Configuration	Dipole
Optical length	$\approx 2.7\,$m
Bending angle	$25\,^{\circ}$
Momentum range	$200 - 900$, MeV
Momentum acceptance	$-0.6 \leq \delta_{Tg} \leq 0.8$
Momentum resolution	$1.6\,\%$
Angular acceptance	
Horizontal	$\approx 240\,$mrad
Vertical	$\approx 500\,$mrad
Angular resolution	
Horizontal	$7\,$mrad
Vertical	$16\,$mrad
Vertex resolution	$1.2\,$cm



- Two **MWDCs** for tracking; Each MWDC consists of 6 wire planes u,u′,v,v′,x,x′

- Two Scintillation planes **E/dE** for PID and supplementary Energy determination

My involvement in the experiment

BEFORE THE EXPERIMENT:

- Calculation of Energy Losses
  Needed for positioning of the exp. equipment and possible use of He bags
- Help with the analysis software
  Developed event viewer to help debugging track reconstruction code.
- Analytical optics module
  Analytical descrip. of particle transport through BB for on-line data analysis
- Setup of BigBite E/dE detector
  Connecting PMTs to electronics, adjusting HVs, tests with cosmics.
- **Trigger Electronics**
  Building BB triggering circuit, coincidence trigger, threshold setup, various tests
- Target setup
  Target installation, optics system setup
  Water calibration, compass measurements

DURING THE EXPERIMENT:

- Monitor performance of DAQ
  Trigger selec., DTM, scalers, data quality
- Handling with BigBite
  HV adjustments, sieve-slit, HV-trips
- Target manipulation
  Tgt. movement, laser operation, pol. meas.

DATA ANALYSIS:

- Compass analysis
  True target orientation at given currents
- Calibration of detectors
  BPM, BCM, BB-E/dE (ADCs, TDCs), Beam En.
- Trigger and scaler analysis
  Good/Random Coincidence, true/false asym.
- **BigBite optics calibration**
  Optics matrix for BB (for the first time)
- **Analysis of production data**
  Asymetries for ^{3}He(e,e'd) and ^{3}He(e,e'p)

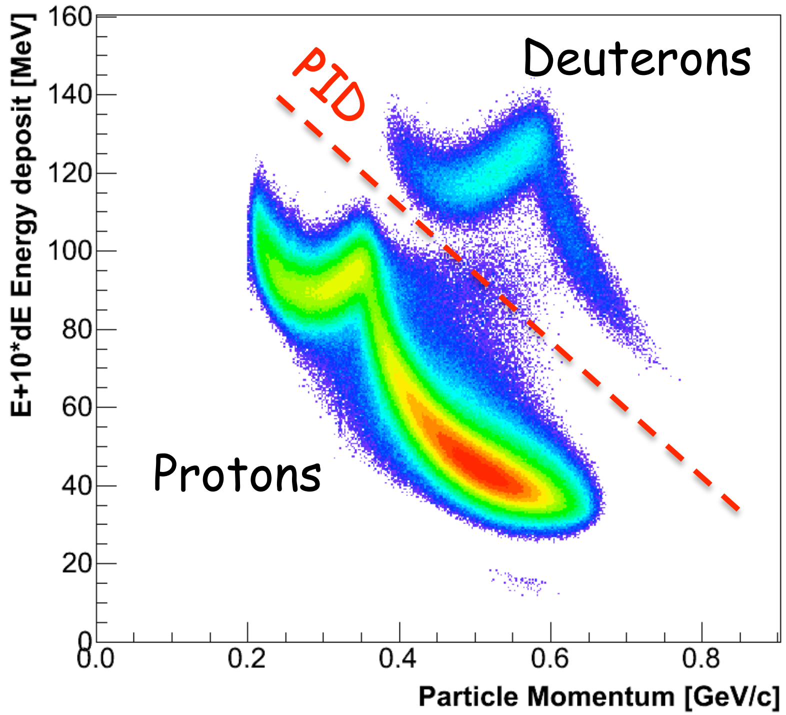
E/dE calibration and PID

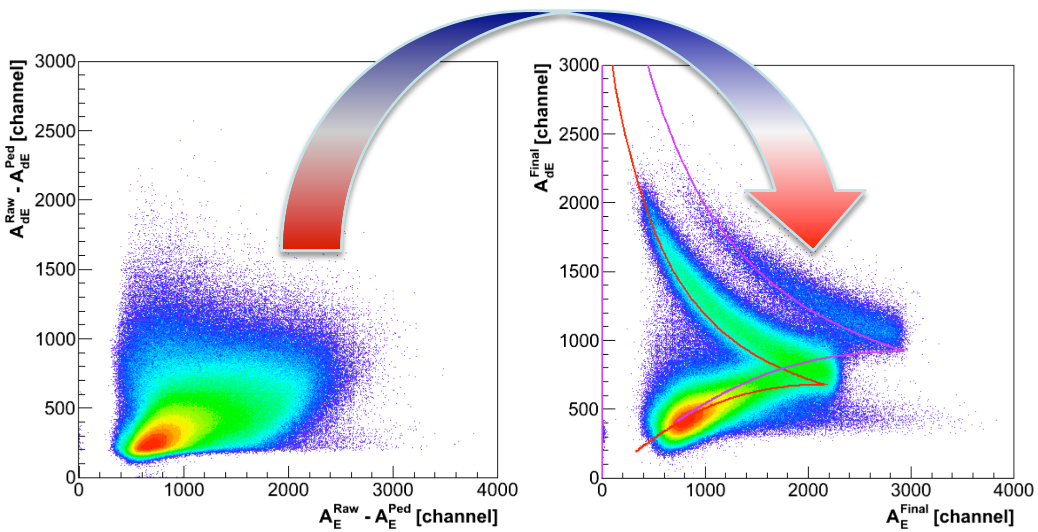
- The information from PMTs is read by **ADCs** (charge) and **TDCs** (timing)

- Timing information required for horizontal positioning and time-of-flight (PID?)

- Charge information used for positioning (attenuations), **PID!**

- Instead of E/dE plots **E+dE vs. p** considered for PID





TDC: - Left/Right calibration

ADC: - Left/Right + between paddles calibration

- Attenuations along scint

- Energy-losses simulation for energy scale

BigBite Optics Calibration

- Purpose of optics calibration is to determine target variables (y_{Tg}, φ_{Tg}, θ_{Tg}, δ_{Tg}) from detector variables (x_{Det}, y_{Det}, θ_{Det}, φ_{Det}).

$$\Omega_{\mathrm{Tg}} = \sum_{i,j,k,l} a_{ijkl}^{\Omega_{\mathrm{Tg}}} x_{\mathrm{Det}}^{i}\, \theta_{\mathrm{Det}}^{j}\, y_{\mathrm{Det}}^{k}\, \phi_{\mathrm{Det}}^{l}\,, \qquad \Omega_{\mathrm{Tg}} \in \{\delta_{\mathrm{Tg}}, \theta_{\mathrm{Tg}}, \phi_{\mathrm{Tg}}, y_{\mathrm{Tg}}\}$$

Knowing optics is equivalent to determining coefficients a_{ijkl}

- Two approaches for finding matrix: Simplex (N&M) and **SVD:**

A set of calibration events can be written as:

$$\underbrace{\begin{pmatrix} 1 & \phi_{(1)} & \cdots & x_{(1)}\theta_{(1)}y_{(1)}\phi_{(1)} \\ 1 & \phi_{(2)} & \cdots & x_{(2)}\theta_{(2)}y_{(2)}\phi_{(2)} \\ 1 & \phi_{(3)} & \cdots & x_{(3)}\theta_{(3)}y_{(3)}\phi_{(3)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \phi_{(N-2)} & \cdots & x_{(N-2)}\theta_{(N-2)}y_{(N-2)}\phi_{(N-2)} \\ 1 & \phi_{(N-1)} & \cdots & x_{(N-1)}\theta_{(N-1)}y_{(N-1)}\phi_{(N-1)} \\ 1 & \phi_{(N)} & \cdots & x_{(N)}\theta_{(N)}y_{(N)}\phi_{(N)} \end{pmatrix}}_{A} \underbrace{\begin{pmatrix} a_{0000} \\ a_{0001} \\ \vdots \\ a_{1111} \end{pmatrix}}_{a} = \underbrace{\begin{pmatrix} y_{\mathrm{Tg}(1)} \\ y_{\mathrm{Tg}(2)} \\ y_{\mathrm{Tg}(3)} \\ \vdots \\ y_{\mathrm{Tg}(N-2)} \\ y_{\mathrm{Tg}(N-1)} \\ y_{\mathrm{Tg}(N)} \end{pmatrix}}_{b}$$

(Learned about SVD from M.O.D. in Bosen 2010)

Condition:

$$\chi^2 = \sqrt{\left|A\,\vec{a} - \vec{b}\right|^2}$$

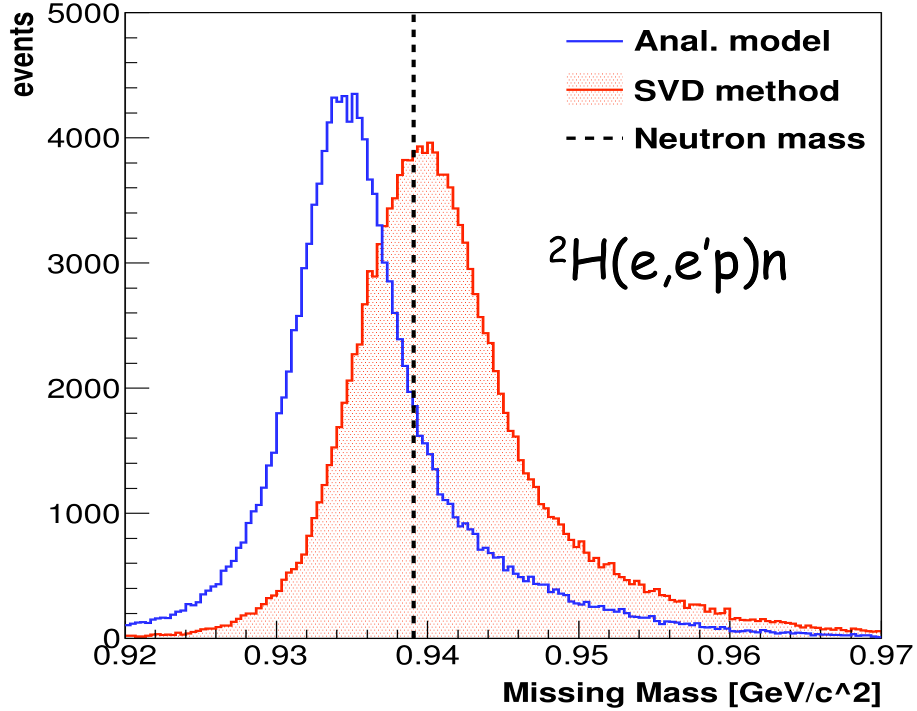
SVD:

$$A = UWV^{\mathrm{T}},$$

Result:

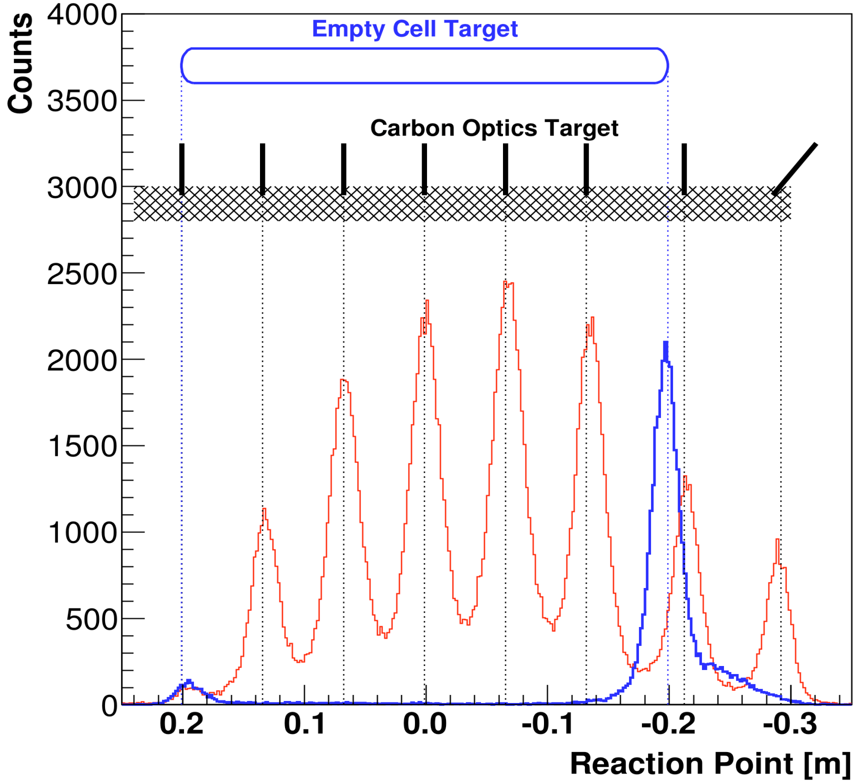
$$\vec{a} = \sum_{i=1}^{M} \left(\frac{\vec{U}_i \cdot \vec{b}}{w_i}\right) \vec{V}_i$$

BigBite Optics Calibration #2



Calibration results for y_{Tg}:

- 7-foil carbon target was used
- Ended with 37 matrix elements
- Positions of foils exactly known
- Resolution σ_y~ 1.1cm



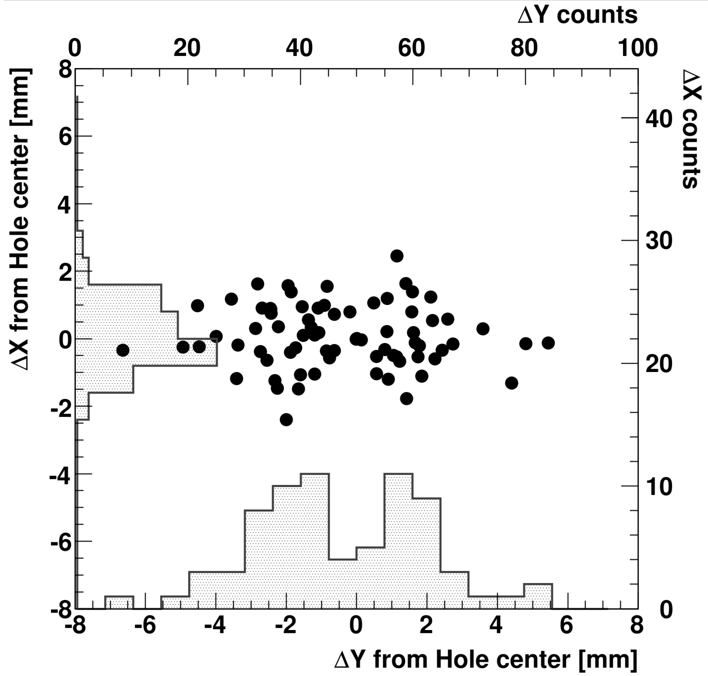
Calibration results for δ_{Tg}:

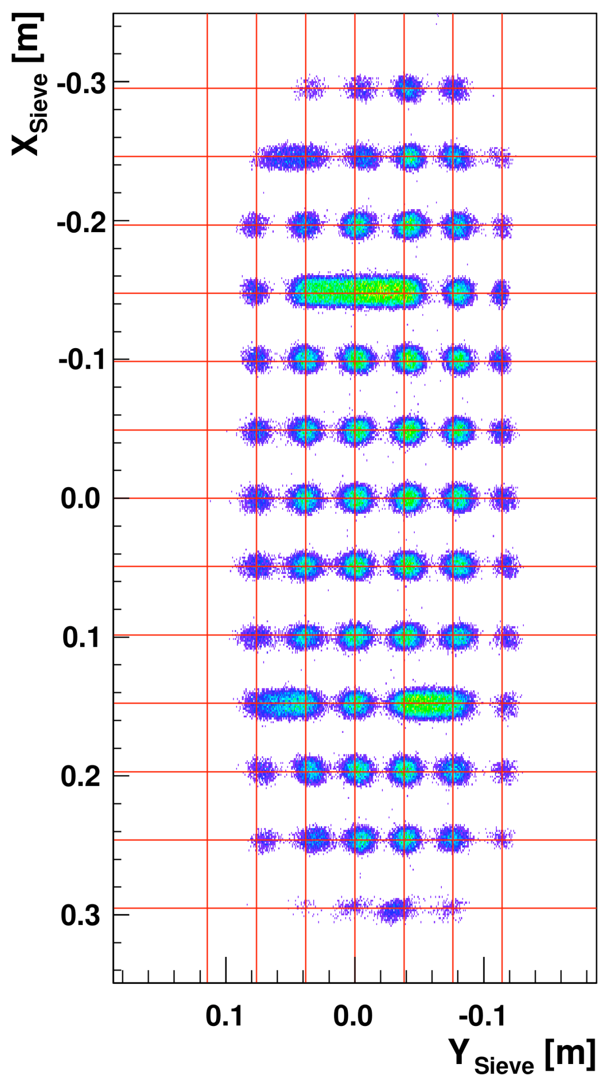
- Both elastic H,D and QE data.
- Only X_{Det}, θ_{Det} dependence
- Finish with 21 matrix elements
- Resolution σ_p/p ~ 1.6% (2%)

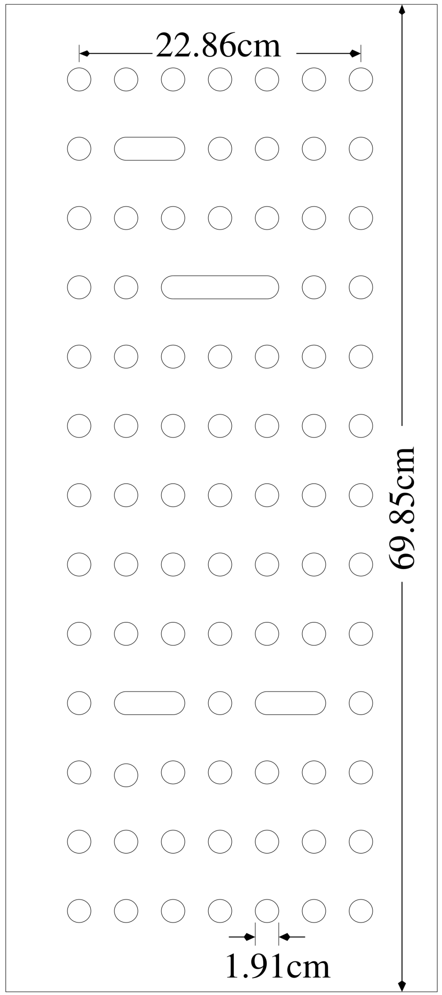
BigBite Optics Calibration #3

Results of optical calibration for θ_{Tg} and ϕ_{Tg} using **sieve-slit** data:

- End with **37** and **51** M.E.
- Resolution ~ 10mrad
- ϕ_{Tg} was most difficult to determine. Deformations visible at the edges.





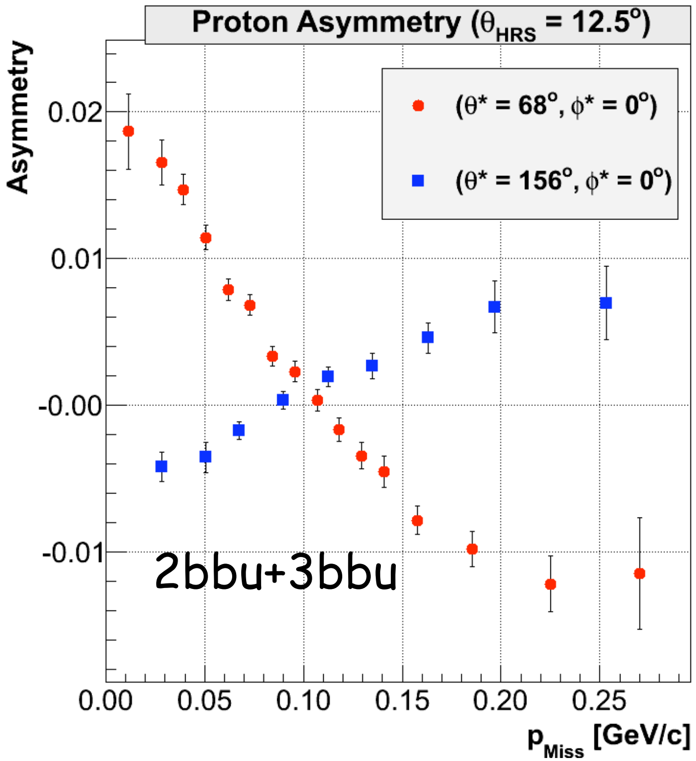


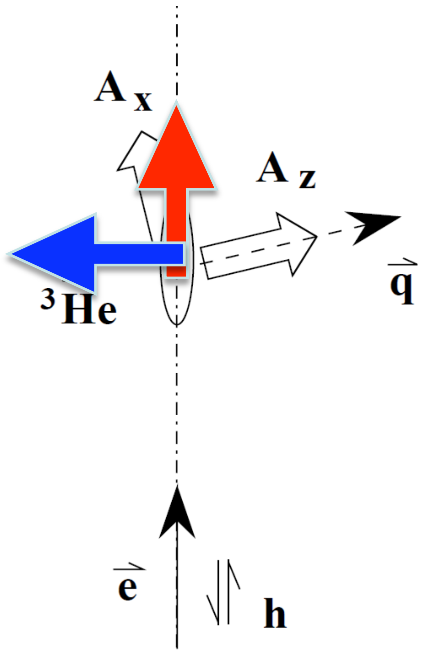
M.Mihovilovic et al., submitted to NIM A

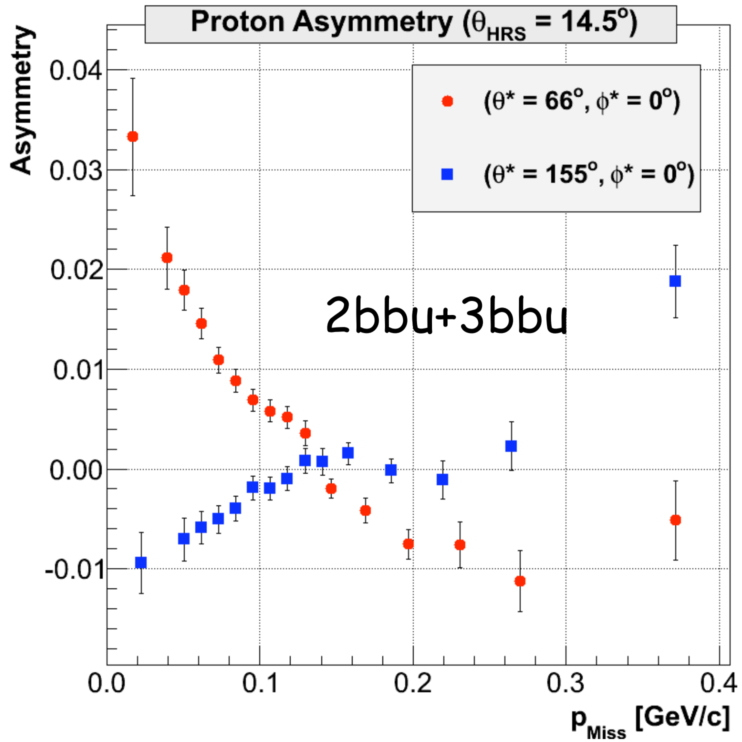
Preliminary Results for $^3\vec{He}(\vec{e},e'p)$

A. E_{beam} = 2.4255 GeV
ω = 100-200MeV,
Q^2=0.2-0.3$(GeV/c)^2$

B. E_{beam} = 2.4255 GeV
ω = 150-250MeV,
Q^2=0.3-0.4$(GeV/c)^2$



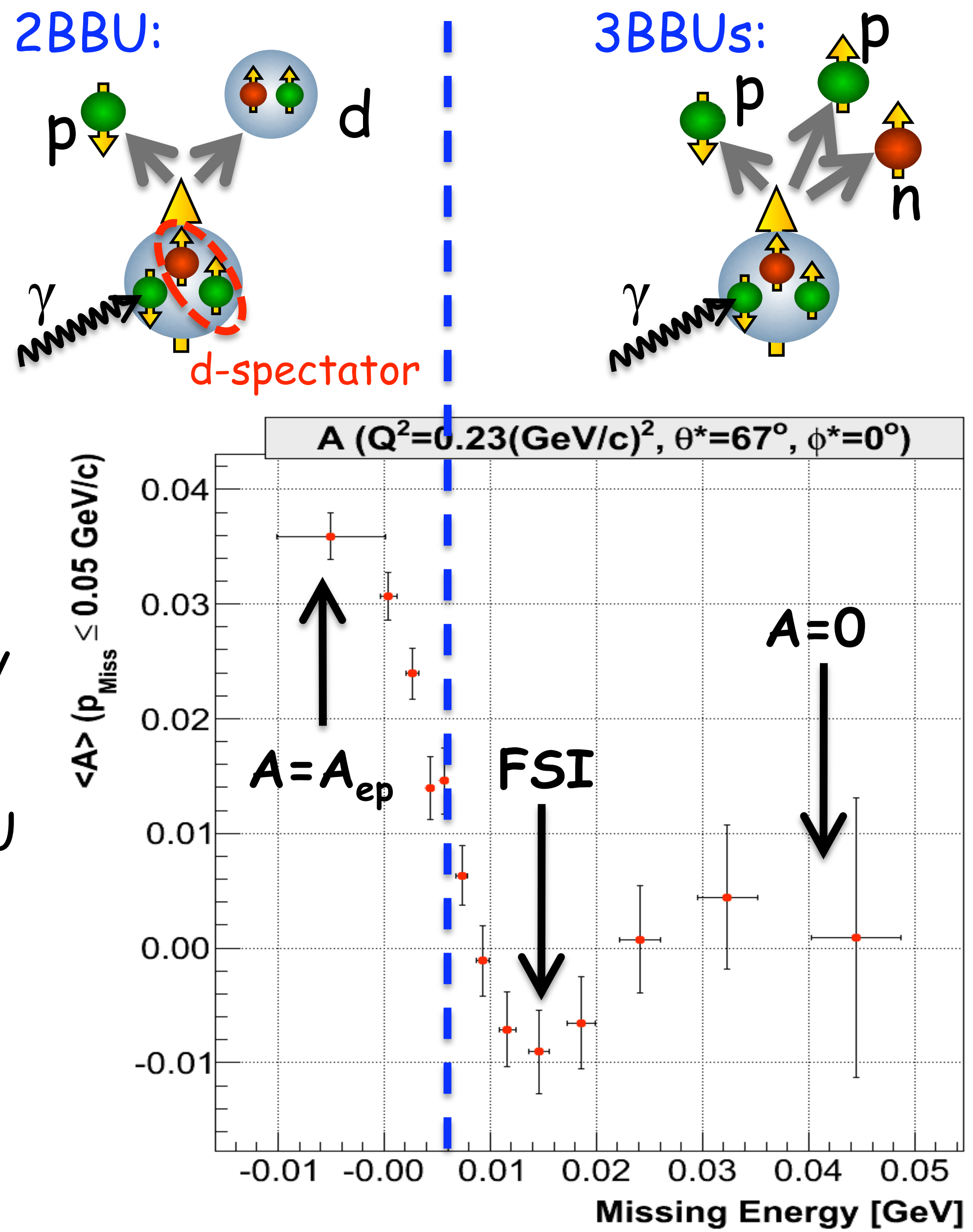




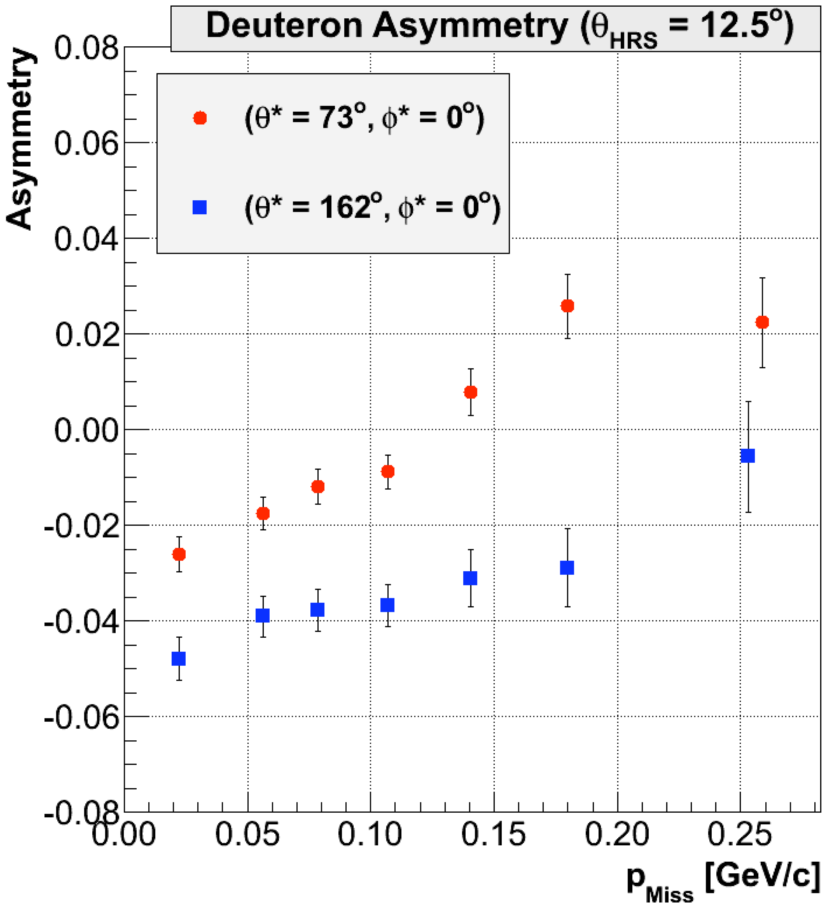
PRESENTLY: Working on the interpretation of the results and trying to compare them to the theoretical predictions

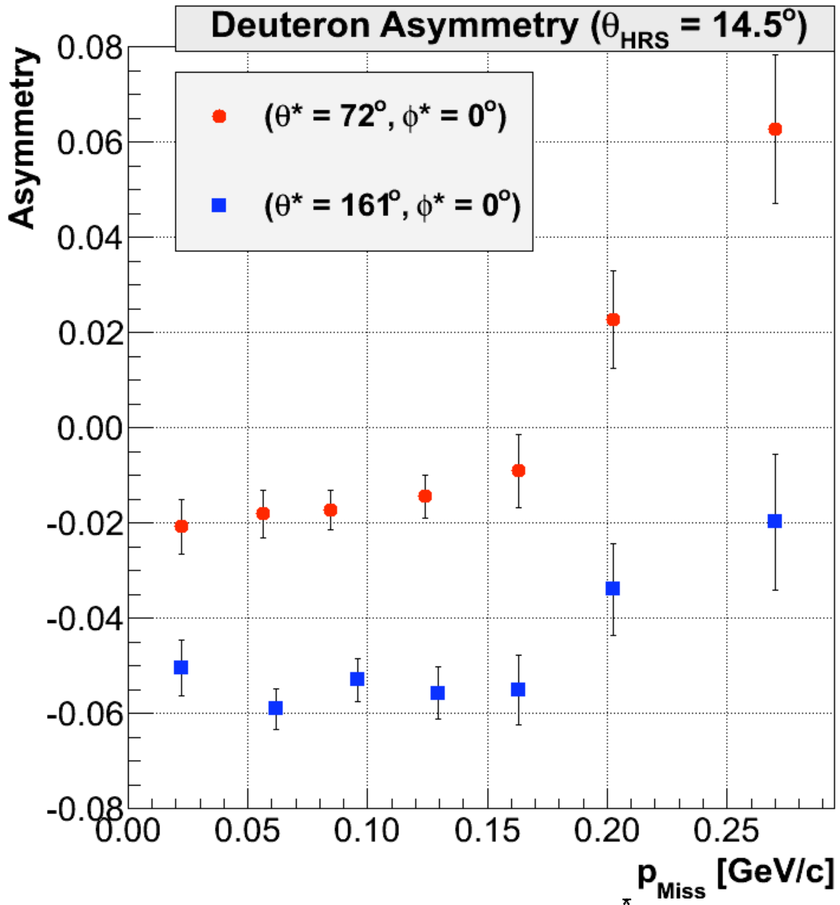
Hand-waving interpretation – proton channel

- A simple picture for $p_{miss} \sim 0$.
- S-state dominates
- Consider only tree diagram
- **Missing Energy = $\omega - T_d - T_p$**
- Negative values due to <u>resolution.</u>
- **<u>Low E_{Miss}</u>** region dominated by 2BBU (A->elastic e-p asym.),
- **<u>High E_{Miss}</u>** dominated by 3BBU (A->0).
- Non-zero asymmetry in 3BBU caused by **<u>FSI</u>** not S'

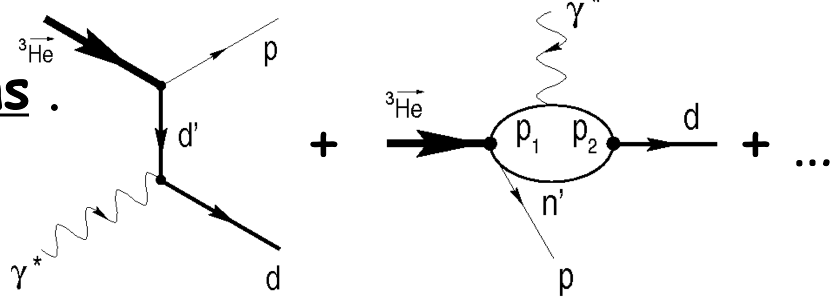


Preliminary Results for $^3\vec{He}(\vec{e},e'd)$





These results require **full calculations** .
Intuitive explanations not possible.
Tree diagram not sufficient



Conclusions

- Asymmetries give an insight to the properties of the nucleus that were not measurable with unpolarized experiments.

- **Why is experiment E05-102 so special?**

1.) Double polarized experiment (^{3}He and e)

2.) Measured all three **(p,d,n)** channels at same Q^2 with ω covering the whole QE peak and more.

3.) Measured asymmetries as function of $p_{miss.}$

First experiment where D-wave and S'-wave contributions to ^{3}He will be inspected in detail in order to understand **Spin, Iso-Spin structure of Nuclei**. Very important for all further experiments on ^{3}He and the neutron.


Thank you for listening!

All about EVe

EVe is a BigBite event display

- Based of CERN Root
  (graphics classes)

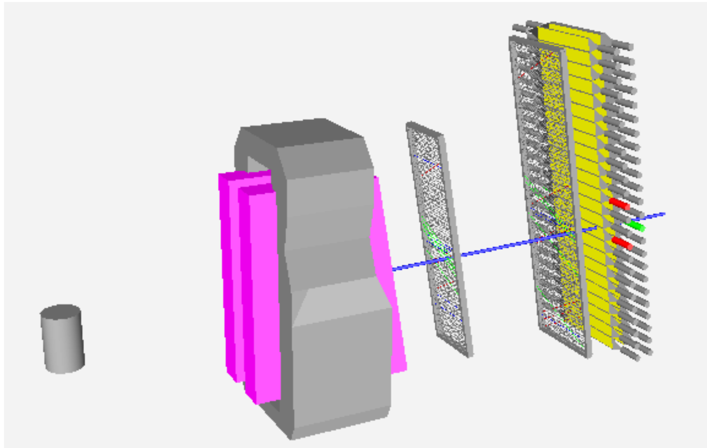
- <u>Not</u> part of the standard
  Root Event Viewer

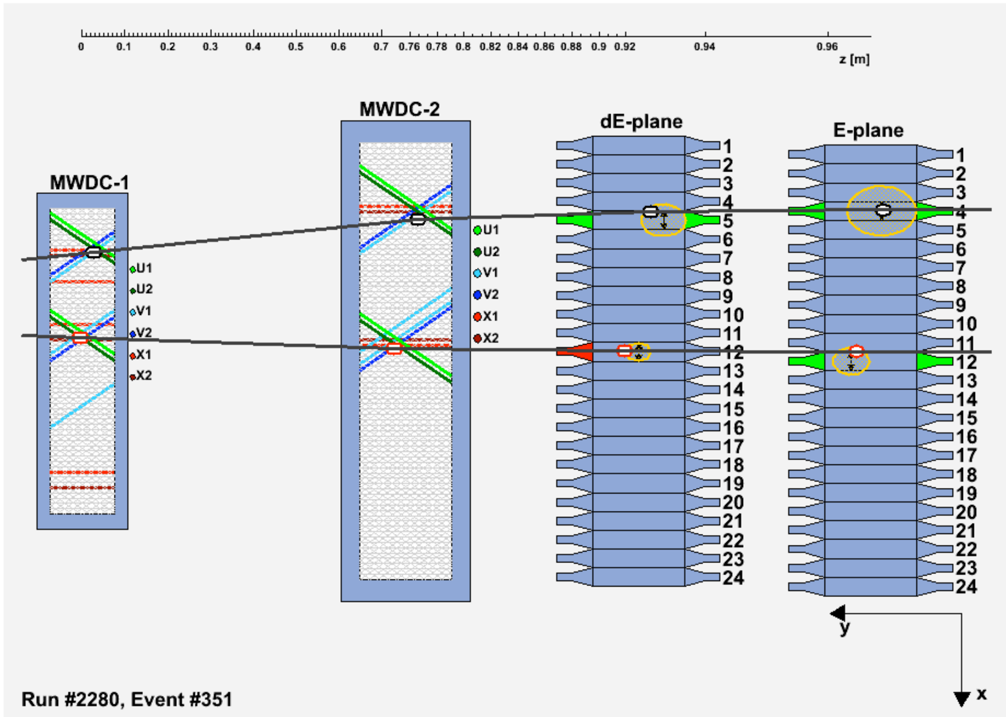
- It shows **hits in all BigBite detectors**

- Supports **2D** and **3D** view

- Used for debugging BigBite tracking algorithm

- Sanity checks during exp.



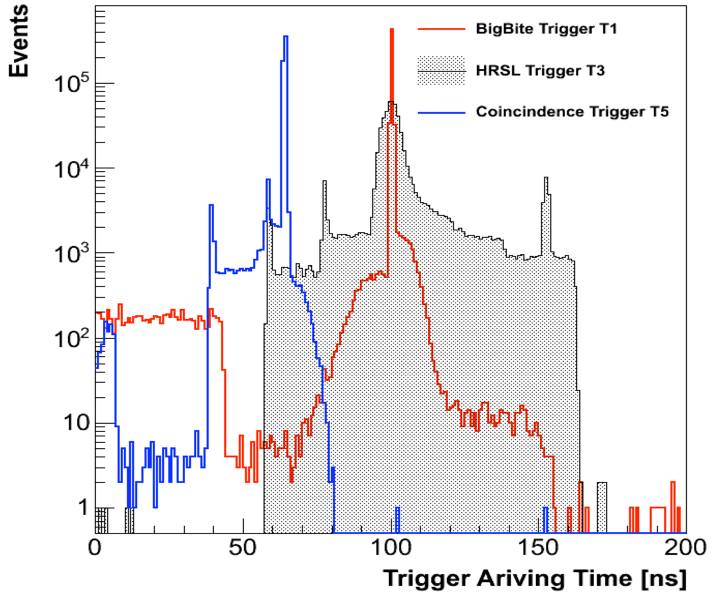


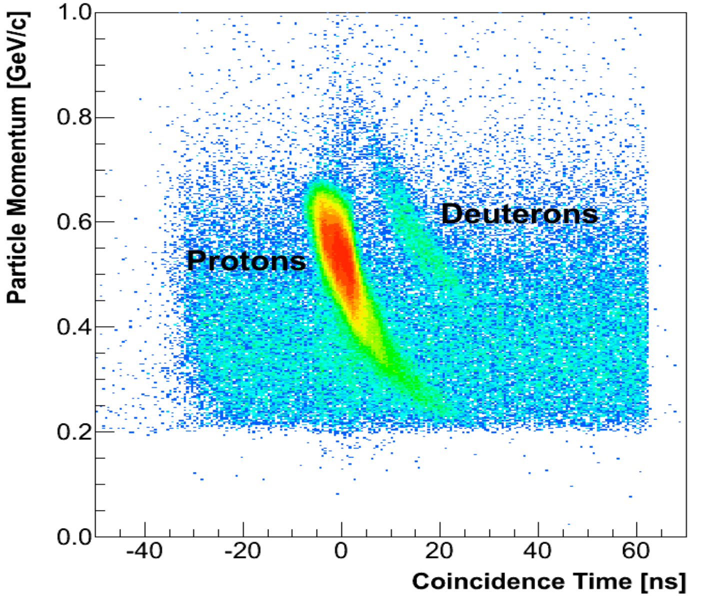
Triggering system

- **<u>Crucial part of the experiment</u>**
- Triggers are formed when a particle hits the detector
- Different combinations of triggers correspond to <u>different types of events</u> (singles, coincidences)
- Triggering circuit (NIM, CAMAC, TS) selects proper events to be recorded.
- **<u>Eight triggers</u>** were considered

T1,**T2** – BigBite Singles; **T3**,**T4** – HRSL Singles; **T5**,**T6** – Coincidences; **T7**- Cosmics; **T8**-Pulser

- Considered **<u>re-timing circuit</u>** (T1 sharp)
- Trigger structure **<u>far more complex</u>** than expected. Need to understand!
- Raw coincidence triggers allow **<u>basic PID</u>**.



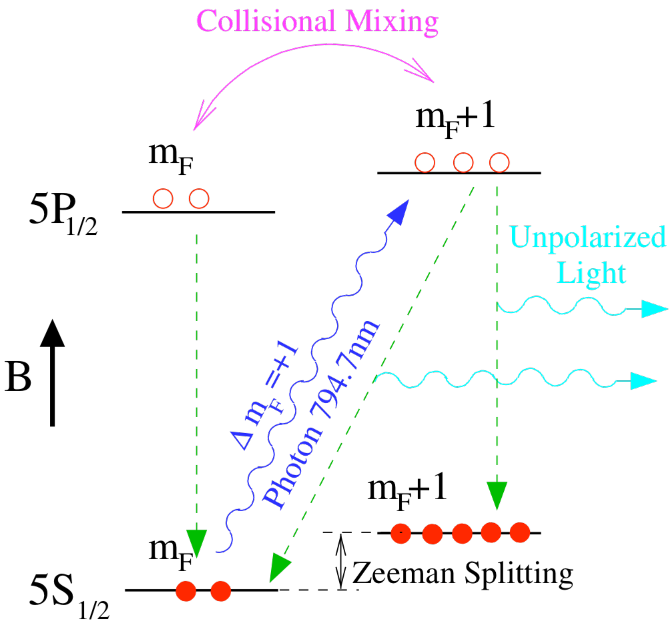


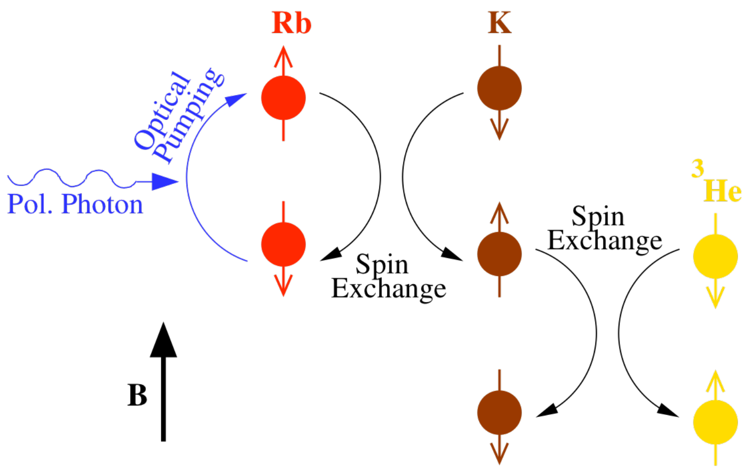
Hybrid Spin Exchange Optical Pumping

^{3}He is polarized through **SEOP**. It is a two step method:

1.) Polarization of Rb vapors with laser:

- Split states (H-F structure, Zeeman)
- **$5S_{1/2}$** -> **$5P_{1/2}$** with c.p. light (Δm_F=1)
- One state gets saturated
- Depolarization ($\Delta m_F \neq 1$) Nitrogen Quenching





2.) Spin-exchange via Hyper-fine interaction between Rb electrons and ^{3}He nucleus (efficiency ~ 2%)

3.) Inclusion of K to increase the polarization efficiency (~ 20%)

2BBU vs. 3BBU Separation

- Theory given separately for 2BBU and 3BBU
- 3BBU hidden beneath the 2BBU.
- Monte-Carlo required for correct interpretation of 3BBU results.
- MCEEP overestimates the 2BBU and underestimates the widths.